Inclusive Charm Production at HERA and the Charm Content of the Photon[1]

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Abstract

We calculate the contribution to inclusive high tranverse momentum (p_T) charm production at HERA from the excitation of charm in the photon. At large values of p_T the results of such a calculation, in the structure function language, will be more reliable as it sums the large logs, $\log(p_T^2/m_c^2)$, as opposed to calculating the contribution of the $2 \rightarrow 3$ subprocess in fixed order of perturbation theory. We find that this contribution is large and comparable to the contribution from γg fusion production of charm. Suitable cuts on the rapidity of the 'away-side' large p_T jet allow a very neat separation between the contributions from the excitation process and from pair-production. We further find that including this excitation contribution we can reproduce the measured inclusive D^* and μ cross–sections measured by the ZEUS and H1 collaborations respectively, in a LO calculation.

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Measurements of F_2^γ in $\gamma^*\gamma$ scattering at the e^+e^- colliders PEP, PETRA, TRISTAN and LEP [1] have by now yielded a lot of information on the parton content of the photon over a wide range of x and Q^2. However, these measurements give direct information only about the quark content of the photon. The gluon density $g^\gamma(x, Q^2)$ is poorly determined as it affects F_2^γ only through the QCD evolution equations. At the current values of Q^2 the charm quark contribution to F_2^γ is approximated by the quark-parton-model (QPM) matrix elements for the process $\gamma\gamma^* \rightarrow c\bar{c}$ and $\gamma^*g^\gamma \rightarrow c\bar{c}$. Through the latter process, the effective charm content of the photon becomes sensitive to $g^\gamma(x, Q^2)$. At larger values of Q^2, $c^\gamma(x, Q^2)$ computed using the massive Altarelli-Parisi (AP) evoultion equations, is considerably different from the pure QPM predictions [2]. A study of the charm content of the photon might also help shed some light on the correct treatment of a heavy parton inside a target. The various different available parametrisations of $q^\gamma(x, Q^2)$ and $g^\gamma(x, Q^2)$ [3] treat the charm density $c^\gamma(x, Q^2)$ with varying amount of rigour and care. It is therefore interesting to take a phenomenological approach and think of measurements which will probe $c^\gamma(x, Q^2)$ directly and hence perhaps also yield information about $g^\gamma(x, Q^2)$.

One possibility is to study production of single charm in ep collisions via the excitation processes (the subprocesses being $c^\gamma + q^p \rightarrow c + q$ and $c^\gamma + g \rightarrow c + g$, here we neglect the contribution coming from charm in the proton) shown in fig. **??**. This will give rise to a single high$-p_T$ charm particle whose transverse momentum is balanced by a light q/g jet. Of course the use of structure functions to compute this process is meaningful only for large values of the p_T of the charm quark. Admittedly for lower values of p_T the more reliable computation will be that of the $2 \rightarrow 3$ subprocesses (some of which are shown in fig. 2), but at larger values of p_T the structure function language sums up the large $\log(p_T^2/m_c^2)$ terms and hence is more accurate. Another contribution to the inclusive charm signal comes from $c\bar{c}$ pair production, via the 'direct' γg fusion subprocess as well as the 'resolved' processes, where the balancing high-p_T jet is the c ($\bar{c}$) quark jet.

The excitation contribution of diagrams in fig. **??** is given, in the Weizsäcker-Williams (WW) approximation, by

$$\frac{d\sigma^{exc}}{dp_T} = \sum_{P_1} \int_{z_{min}}^{z_{max}} f_{\gamma|e}(z) \, dz \, \int_{x_\gamma^{min}}^1 f_{c|\gamma}(x_\gamma)dx_\gamma$$

$$\cdot \int_{x_p^{min}}^1 f_{P_1|p}(x_p)dx_p \, \frac{d\hat{\sigma}}{dp_T}(P_1 + c^\gamma \rightarrow c + P_1), \tag{1}$$

where $f_{\gamma|e}$, $f_{c|\gamma}$ and $f_{P_1|p}$ represent the flux factors of the γ in the electron, charm in the photon and parton P_1 in proton respectively;

$$z_{min} = \max\{z_{min}^{kin}, z_{min}^{exp}\}$$

$$z_{max} = \min\{z_{max}^{exp}, 1\},$$

where $z_{min(max)}^{exp}$ correspond to the experimental cuts on the outgoing electron (or equivalently the γ energy) and $z_{min}^{kin}, x_\gamma^{min}$ and x_p^{min} correspond to the kinematic limits on the different momentum fractions. The direct contribution to $c\bar{c}$ pair production is similarly given by

$$\frac{d\sigma^{pair}}{dp_T} = \int_{z_{min}}^{z_{max}} f_{\gamma|e}(z) \, dz \, \int_{x_p^{min}}^1 f_{g/p}(x_p)dx_p \, \frac{d\hat{\sigma}}{dp_T}(\gamma + g \rightarrow c + \bar{c}), \tag{2}$$

where $f_{g/p}$ represents the gluon flux in the proton, and the 'resolved' contribution is given by an expression similar to Eq.(1) where contributions from all the various subprocesses involving all the different partons in the photon are to be included. We use LO expressions for all the $2 \to 2$ subprocess cross–sections [3].

The virtuality $-P^2$ of the exchanged photon in figs. ?? and 2 can, in principle, affect its parton content [4]. For the results presented here we impose the requirement $P^2 <$ 0.01 GeV^2 and $0.25 < z < 0.70$, following the cuts used in the experimental study of the photoproduction of jets [5]. This implies that our expression for the photon flux factor is given by

$$f_{\gamma|e} = \frac{\alpha}{2\pi z}[1 + (1 - z)^2] \ \ln\left(\frac{0.01 \text{ GeV}^2}{P^2_{min}}\right) \ - \ \frac{\alpha}{\pi}\frac{1 - z}{z}, \tag{3}$$

where

$$P^2_{min} = m_e^2 \frac{z^2}{(1 - z)}.$$

As a result of the cut on P^2 we can neglect the effect of the virtuality of the γ on its parton content.

The results of our computations are shown in fig. ?? for various photon structure function parametrisations DG [6], LAC[7], WHIT[2] and different proton structure functions [8]; we use $\Lambda_{QCD} = 0.4$ GeV for the DG and WHIT parametrizations, and 0.2 GeV for LAC. We see from this figure that the excitation cross–sections are indeed comparable to the $c\bar{c}$ production cross–sections. This implies that while the 'resolved' contribution to $c\bar{c}$ pair production is small (as shown by the long dashed line) for these large values of p_T, the inclusive charm signal still has a considerable 'resolved' component due to the excitation contribution. Though we do not show them separately here, the contribution to σ^{exc} coming from a gluon in the initial state dominates over most of the p_T range. Apart from the DG parametrisation for which excitation contributions are about a factor 2 higher than the rest, the charm excitation cross–section at HERA seems to be fairly independent of both the photon and the proton structure function parametrisations. Since the DG parametrisation has $c^\gamma = u^\gamma$ it definitely overestimates the charm excitation and hence this part of the result is easily understood. In principle, the other parametrisations of $c^\gamma(x, Q^2)$ do also look quite different, both in the small and large x_γ region, but the effective $c-$quark content of the electron, which involves the convolution of this with the WW function is very similar in the end; this is reflected in the similarity of the predictions using the LAC and WHIT parametrizations for $c^\gamma(x, Q^2)$. This can be looked upon as a positive point in that the size of the excitation contribution to the inclusive charm signal, at large p_T, can be estimated quite reliably. However, it is also clear that one needs to devise kinematic cuts to separate the excitation contribution to the inclusive charm signal from that due to $c\bar{c}$ pair production. (This is also necessary if direct $c\bar{c}$ pair production is to be used to study the gluon density in the proton.)

To this end, we next study the kinematic distributions of the decay muon which is used to tag the charm in the final state and also that of the balancing ('away–side') jet. In this calculation we include fragmentation of the $c-$quark into a charmed meson à la Peterson fragmentation function [9] with the parameter ϵ as given in ref.[10], and use the value 0.1 for the semileptonic branching ratio of the charmed hadrons. Since, for our p_T cut, $c\bar{c}$ production is dominated by the 'direct' process, the real kinematical difference between

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the excitation and $c\bar{c}$ contributions to the charm signal comes from the fact that in the excitation process only a fraction of the γ energy is available for the subprocess, whereas in the 'direct' process all of it goes into the subprocess. As a result, the direct process on the whole receives contributions from smaller x_p values than the excitation process does. Hence the $\bar{c}$ jet in the $c\bar{c}$ case will have much more negative rapidity than the 'light' (q/g) jet in the excitation process (the proton direction is taken as positive z axis); this is very similar to the corresponding situation with the photoproduction of jets [3]. On the other hand, the rapidity distributions of the charm quarks produced in both the excitation and pair production processes are very similar and hence those of the decay muons also. The kinematic distribution in p_T^μ and y_μ therefore are very similar for both contributions. Fig. 4 shows the rapidity distribution of the jet balancing the large p_T charm, with the WHIT5 parametrisations of $q^\gamma(x, Q^2)$ and $g^\gamma(x, Q^2)$ and MRSD- for the proton structure function. As we can see very clearly from the figure, a cut on $y_{jet} < 0.5$ can neatly separate the excitation and the $c\bar{c}$ contribution from each other. The rates presented in the figure include the semileptonic branching ratio of the charm meson. It should also be mentioned that these distributions do have some sensitivity to c^γ, but only for negative values of y_{jet} where the signal is dominated by the $c\bar{c}$ contribution. The figure also tells us that the signal is healthy even after these cuts and hence is measurable. For a clear signal one will have to make an additional cut on p_T^μ as well but that will affect both the excitation and the pair production contribution similarly.

Recently both H1 and ZEUS have reported measurements of inclusive charm production at HERA [11]. ZEUS reports D^* production with $p_T(D^*) > 1.7$ GeV and $|\eta(D^*)| < 1.5$ where η is the pseudorapidity with $P^2 < 4$ GeV^2 and $0.15 < z < 0.86$, whereas H1 reports observation of events with a hard muon with $p_T^\mu > 1.5$ GeV and $30° < \theta(\mu) < 130°$. The ZEUS analysis then uses this measured cross–section to estimate the 'total' $c\bar{c}$ cross–section by extrapolating it outside the measured region and then compare the value so obtained with the QCD NLO calculations. We attempted instead to reproduce the cross–sections measured by ZEUS and H1 by using our LO QCD calculations. Since the p_T cut and m_c are comparable it is not clear whether factorisation of the production and fragmentation of the charm quark is such a good approximation. On the other hand if we include the fragmentation of the $c-$quark in the final state then we must include the excitation contribution which corresponds to the fragmentation of the initial state photon into charm. We therefore run our Monte Carlo with two different options: In one case (A) we fragment the charm using the Peterson fragmentation function and include the excitation contributions whereas in the other case (B) we do not include the fragmentation of the final state c quark and drop the excitation contributions as well. Eventually detailed comparisons with measured transverse momentum and rapidity distributions should reveal which discription is more appropriate. When comparing with ZEUS results we include a factor of 0.26 which is the probability of a charm quark to fragment into a charged D^* meson.

Table 1 gives a summary of our calculations along with the results reported by the two experimental groups. We find that for the ZEUS data, in case A the results become less sensitive to the low-x behaviour of the proton structure function and the excitation contribution actually dominates. In this case both the MRSD- and MRSD0 for the partons in the proton and WHIT5 or LAC1 partons in the photon reproduce the data whereas DG predicts too big a cross–section. On the other hand, in case B, the results are more sensitive

Table 1: The D^* and μ cross–sections measured at HERA by ZEUS and H1, compared with the LO predictions discussed in the text.

ZEUS (D^*)			H1 (μ)		
Data: $32 \pm 7^{+4}_{-7}$ nb			Data: $2.03 \pm 0.43 \pm 0.7$ nb		
A: Frag and c^γ included			A: Frag and c^γ included		
p str.fn.	γ str. fn.	σ (nb)	p str.fn.	γ str. fn.	σ (nb)
MRSD-	LAC1	27.4	MRSD-	LAC1	1.5
MRSD-	WHIT5	26.0	MRSD-	WHIT5	1.5
MRSD0	WHIT5	21.9	MRSD0	WHIT5	1.48
MRSD-	**DG**	64	MRSD-	**DG**	2.9
B: No frag and c^γ not included			B: No frag and c^γ not included		
p str.fn.	γ str. fn.	σ (nb)	p str.fn.	γ str. fn.	σ (nb)
MRSD-	LAC1	26.8	MRSD-	LAC1	1.8
MRSD0	WHIT5	15.4	MRSD0	WHIT5	1.5
MRSD-	WHIT5	37.0	MRSD-	WHIT5	2.4
MRSD-	DG	33.4	MRSD-	DG	2.3

to the low-x behaviour of the parton densities and we find that we can reproduce the cross–section only for a steeply rising gluon density. In this case all the photonic parton densities combined with MRSD- for the proton are acceptable whereas MRSD0 gives answers smaller by a factor 2 for all reasonable choices of the momentum scale as well as the photonic parton densities. For the H1 sample, the p_T^μ cut means that the produced charm quark has much higher p_T than for ZEUS. Again, inclusion of fragmentation reduces the sensitivity to the low-x behaviour of the gluon in the proton and results for various combinations of partons in the photon and proton are almost the same. As before, the DG parametrisation predicts a large cross–section, 2.9 nb, but it is not inconsistent with the data.

In conclusion we have studied the contribution to the inclusive charm signal from the excitation of charm in the photon. We find the rates to be comparable to the contribution coming from $c\bar{c}$ pair production. Due to the convolution with $f_{\gamma|e}$ the sensitivity of σ^{exc} of Eq.(1) to the region of large x_γ, where the various parametrisations for $c^\gamma(x, Q^2)$ differ most, is reduced. This means that this 'resolved' background to the large p_T, inclusive charm signal coming from the 'direct' process can be predicted quite reliably. Making a cut on the 'away-side' jet-rapidity allows a separation of these two contributions. Note that charm excitation events should contain a second 'spectator' charm (anti–)quark in the photon remnant, which has a large, negative rapidity (close to the electron beam direction). In contrast, $c\bar{c}$ pair production events should contain a second high$-p_T$ charm (anti–)quark. In both cases the presence of a second charmed particle should be visible in some fraction of the events; this could be used as a cross–check of the relative sizes of the two contributions to the inclusive charm signal. Even after all the cuts and folding of the cross–sections with various branching fractions, the rates for inclusive charm production are large and easily measurable. Further, a LO computation including the excitation contributions gives results comparable to the recent measurements of the inclusive charm signal by ZEUS and H1. On the theoretical side, it

would be interesting to compare our results with explicit $2 \rightarrow 3$ subprocess calulations and see at what values of p_T do they match.

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